PROBLEMS ENCOUNTERED IN USING ELEVATION POWER SPECTRA AS CRITERIA OF PAVEMENT CONDITION

SEPT. 1965

NO. 14

by

B.E. QUINN

Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

PROBLEMS ENCOUNTERED IN USING ELEVATION POWER SPECTRA AS CRITERIA OF PAVEMENT CONDITION

To: G. A. Leonards, Director
Joint Highway Research Project
September 24, 1965

From: H. L. Michael, Associate Director
Joint Highway Research Project
File: 6-20-6

The attached report is submitted to the Board as information. The research was performed by Professor Bayard E. Quinn of the School of Mechanical Engineering as part of the National Cooperative Highway Research Program Project 1-2. The report authored by Professor Quinn is titled "Problems Encountered in Using Elevation Power Spectra as Criteria of Pavement Condition."

The research did not utilize JHRP funds and is submitted to the Board as information only.

Respectfully submitted,

Harold L Michael

Harold L. Michael, Secretary

HLM:bc

Attachment

Copy:

F. L. Ashbaucher
J. R. Cooper
J. W. Delleur
W. L. Dolch
W. H. Goetz
W. L. Grecco
F. F. Havey
F. S. Hill
J. F. McLaughlin

F. B. Mendenhall
R. D. Miles
J. C. Oppenlander
W. P. Privette
M. B. Scott
J. V. Smythe
F. W. Stubbs
K. B. Woods
E. J. Yoder

Digitized by the Internet Archive
in 2011 with funding from
LYRASIS members and Sloan Foundation; Indiana Department of Transportation

http://www.archive.org/details/problemsencounte00quin

Information Report

PROBLEMS ENCOUNTERED IN USING ELEVATION POWER SPECTRA AS CRITERIA OF PAVEMENT CONDITION

by

Bayard E. Quinn
Research Engineer

School of Mechanical Engineering

File No: 6-20-6

Purdue University

Lafayette, Indiana

September 24, 1965

PROBLEMS ENCOUNTERED IN USING ELEVATION POWER SPECTRA AS CRITERIA OF PAVEMENT CONDITION

(A Supplement to the Final Report of NCHRP Project 1-2)

By
Bayard E. Quinn
SCHOOL OF MECHANICAL ENGINEERING
PURDUE UNIVERSITY

ABSTRACT

Elevation power spectra are calculated for sections of pavement for which Bureau of Public Roads roughometer ratings are available, and these ratings are compared with a criterion of pavement condition based on the computed elevation power spectra. In general, the criterion of pavement condition determined from the power spectrum is less reliable than the criterion of condition determined by the roughometer.

Problems associated with the calculation of elevation power spectra from highway elevation measurements are discussed, and the effects of two different methods for obtaining elevation deviations are shown. The use of a running mean for this purpose is shown to yield more satisfactory results.

Power spectra calculated from data obtained by other devices used to determine highway condition are also included. These devices give good results, although insufficient data are available to form a valid conclusion relative to the performance of these devices.

PROBLEMS ENCOUNTERED IN USING ELEVATION POWER SPECTRA AS CRITERIA OF PAVEMENT CONDITION

A Supplement to the Final Report of

NCHRP Project 1 - 2

by

Bayard E. Quinn
School of Mechanical Engineering

from

Purdue Research Foundation
Lafayette, Indiana

March 1, 1965

TABLE OF CONTENTS

Page

List of Figures ii

Summary of Findings iii

Introduction 1

Problems Encountered in Calculating Elevation Power Spectra From Elevation Measurements 2

Discussion of Results 16

Conclusions 41

References 44

LIST OF FIGURES

Figure	Title	Page
1	Relationship Between Elevation Measurements and Highway Deviations	6
2	Highway Elevation Power Spectra Computed From Elevation Measurements (Rigid Pavement)	17
3	Highway Elevation Power Spectra Computed From Elevation Measurements (Flexible Pavement).	18
4	Highway Elevation Power Spectra Computed From Elevation Measurements (Overlay Pavement)	19
5	Mean Square Deviation Versus BPR Roughometer Rating (Rigid Pavements)	23
6	Mean Square Deviation Versus BPR Roughometer Rating (Flexible Pavements)	24
7	Mean Square Deviation Versus BPR Roughometer Rating (Overlay Pavements)	25
8	Mean Square Deviation Versus Dynamic Tire Force (Rigid Pavements)	29
9	Mean Square Deviation Versus Dynamic Tire Force (Flexible Pavements)	30
10	Mean Square Deviation Versus Dynamic Tire Force (Overlay Pavements)	31
11	Comparison of Elevation Power Spectra	33
12	Power Spectrum Obtained From Truck Mounted Profilometer	36
13	Power Spectrum Obtained From Servo - Seismic System (90 Foot Filter)	38
14	Power Spectrum Obtained From Servo - Seismic System (600 Foot Filter)	40

SUMMARY OF FINDINGS

(1) A more reliable criterion of pavement condition is obtained from the Bureau of Public Roads roughometer than is obtained from a power spectrum calculated from elevation measurements taken under normal field conditions.

(2) The most reliable criterion of pavement condition determined from a power spectrum calculated from elevation measurements was obtained when elevation deviations were calculated from a running mean.

(3) It appears possible to obtain elevation power spectra from special devices, developed for the purpose of measuring pavement condition, but for the devices considered in this report insufficient data are available to form a valid conclusion in this regard.

I. INTRODUCTION

A previous report (1) summarizing the activities conducted under NCHRP Project 1 - 2 was issued in February 1964, in which a comparison was made of different methods for measuring pavement condition. During the time that this investigation was conducted, sufficient information was obtained to permit the calculation of elevation power spectra. This report deals with the problems that are associated with using elevation power spectra as criteria of pavement condition. The objectives of this investigation were as follows:

(1) Investigate various methods for calculating highway power spectra from elevation measurements.

(2) Investigate the possibility of using elevation power spectra as criteria of pavement condition.

(3) Consider the possibility of using other highway measurements in place of elevation measurements to obtain highway power spectra.

With these objectives in mind, further study was conducted of the data collected on NCHRP Project 1 - 2, and the results of this effort are summarized in this report.

A brief explanation of an elevation power spectrum is appropriate at this point.

An elevation power spectrum is a curve (see Figure 2) that shows the extent to which various wave lengths in a longitudinal highway profile contribute to the overall roughness of the highway. The units of wave length are "feet per cycle," but in performing the necessary calculations it is more convenient to use the reciprocal of this quantity which is "cycles per foot". This latter quantity is a distance-based frequency, and is plotted along the horizontal axis as shown in Figure 2.

The area under the power spectrum curve represents the mean square value of the variation in the elevation measurements. If the highway were perfectly smooth (and level), the elevation values would be identical and there would be no variation. The elevation power spectrum for such a highway would therefore coincide with the horizontal axis shown in Figure 2.

For a level highway with some roughness there would be a variation in the elevation measurements. The area under the corresponding elevation power spectrum curve would therefore be equal to the mean square value of the variation in the elevation measurements and would thus have the units of "feet squared." Hopefully it is this quantity that can be used as a criterion of pavement condition.

Since the area under an elevation power spectrum curve will have

the units of "feet squared", and since the frequency in "cycles per foot" is plotted along the horizontal axis, the ordinates of the curve must have the units of "feet squared per cycle per foot" (ft ^{2}/cpf). This quantity is indicated as the elevation power density in Figure 2.

As previously mentioned, the area under the curve should serve as a criterion of pavement condition, since the rougher the highway, the greater will be the variation between adjoining elevation measurements, and hence the larger will be the area bounded by the power spectrum curve and the axes.

Moreover, the area between any two selected frequencies (or wave lengths) represents the contribution (in "feet squared") that that band of frequencies makes to the total roughness of the highway profile. Figure 2 thus indicates that low frequencies (long wave lengths) make the greatest contribution to the overall roughness of the highway profile.

If properly determined, the highway elevation power spectrum should not only indicate the roughness of the highway (total area) but should also indicate the contribution of various wave lengths to the total roughness.

II. PROBLEMS ENCOUNTERED IN CALCULATING ELEVATION POWER SPECTRA FROM ELEVATION MEASUREMENTS

Investigators interested in predicting the behavior of vehicles on highways require a suitable characterization of the highway profile that can serve as an input for their problems. An elevation power spectrum, calculated from highway elevation measurements, has attracted considerable interest for this purpose, and has been considered by many investigators as a means of describing a pavement profile. The chief attraction of the elevation power spectrum is that it can theoretically represent the extent to which various wavelengths exist in a highway profile. In addition, it can be used with suitable vehicle characteristics to predict the behavior of the vehicle. For these reasons the power spectrum has received considerable attention.

If the elevation power spectrum is to serve as a detailed description of the pavement profile, it must correlate with other criteria of pavement condition. Fortunately it is possible to summarize the description afforded by an elevation power spectrum by considering the total area under the power spectrum curve. This gives the mean square value of the variation in the pavement profile, and thus a single number is available from the power spectrum as well as a more detailed description of the pavement profile. One purpose of this investigation was therefore to compare this criterion of pavement condition obtained from the elevation power spectrum with other criteria obtained for the same length of pavement. It is therefore appropriate to discuss some of the major

problems that are encountered when calculating an elevation power spectrum since different ways of meeting these problems will result in the calculation of different elevation spectra for the same highway profile.

A. Accuracy of Elevation Measurements

The first question encountered is that of the accuracy with which highway elevation measurements must be made. This is a difficult question because the problem arises of determining the amplitude of the wavelengths that are to be observed in these measurements. If these wavelengths are of small amplitude then the elevation measurements must be made with a relatively high degree of accuracy. On the other hand if the amplitude to be observed is relatively large, then a greater degree of error is permissable. In answering this question it is therefore important to know the purpose for which the resulting power spectrum will be used in order to set allowable tolerances for the elevation measurements.

In previous publications (2) (3) the use of elevation power spectra as highway characterizations in predicting dynamic vehicle forces has been discussed. In this case the vehicle characteristics indicate the degree of accuracy that must be maintained in characterizing a highway with a power spectrum. This condition is revealed by the fact that the vehicle characteristics indicate that the vehicle is sensitive to long wavelength disturbances that cause excessive motion of the sprung mass of the vehicle. It

is therefore desirable that an elevation power spectrum accurately represent wavelengths that contribute to this type of vehicle motion. Since long wavelengths usually have large amplitudes, the measurement of these disturbances in the highway profile offers no special problem.

On the other hand the vehicle characteristics indicate that the vehicle is very sensitive to short wavelengths that produce wheel hop, or appreciable motion of the unsprung mass of the vehicle. Unfortunately these short wavelengths are usually of relatively small amplitude, and hence must be measured with a highdegree of accuracy. The extreme sensitivity of the vehicle to these disturbances indicates that error in measuring short undulations can produce appreciable error in the predicted forces.

If on the other hand the vehicle is not sensitive to short wavelengths then error in these disturbances will not affect the response of the vehicle to any appreciable extent. As a result it would not be necessary to measure the small wavelengths with a high degree of precision.

Thus it is not possible to give a single rule concerning the accuracy with which elevation measurements must be made when they are to be used for calculating an elevation power spectrum. An indication of the level of accuracy that is required is indicated in the results obtained from this investigation.

B. Technique to be Used for Removing Long Wavelengths

The calculation of an elevation power spectrum of a highway consists basically of two important steps. The first of these involves selecting the preliminary processing technique to be used on the elevation measurements (obtained with rod and level) to prepare them for the power spectrum calculation, while the second step is that of performing the power spectrum calculation after suitable input data have been obtained.

The problem of selecting an appropriate data preprocessing procedure is best discussed by referring to Figure 1. In this figure the original grade line of a perfectly smooth highway is indicated as a portion of a sine wave. This could be caused by the highway going over the crest of a hill. Elevation measurements of the profile would indicate the existence of a sine wave having an enormous amplitude and an extremely large wavelength. If the pavement surface is perfectly smooth, this should not be reflected in a criterion of the pavement condition. As a result, it is therefore necessary to remove this effect from original elevation measurements if a valid criterion of the condition of the pavement is to be obtained. If after several years of use the present highway profile is as indicated, it is apparent that the original surface of the pavement has been modified. A criterion of pavement condition must therefore be based upon the difference between the original profile and the present profile and as a consequence, deviations of the present highway from the

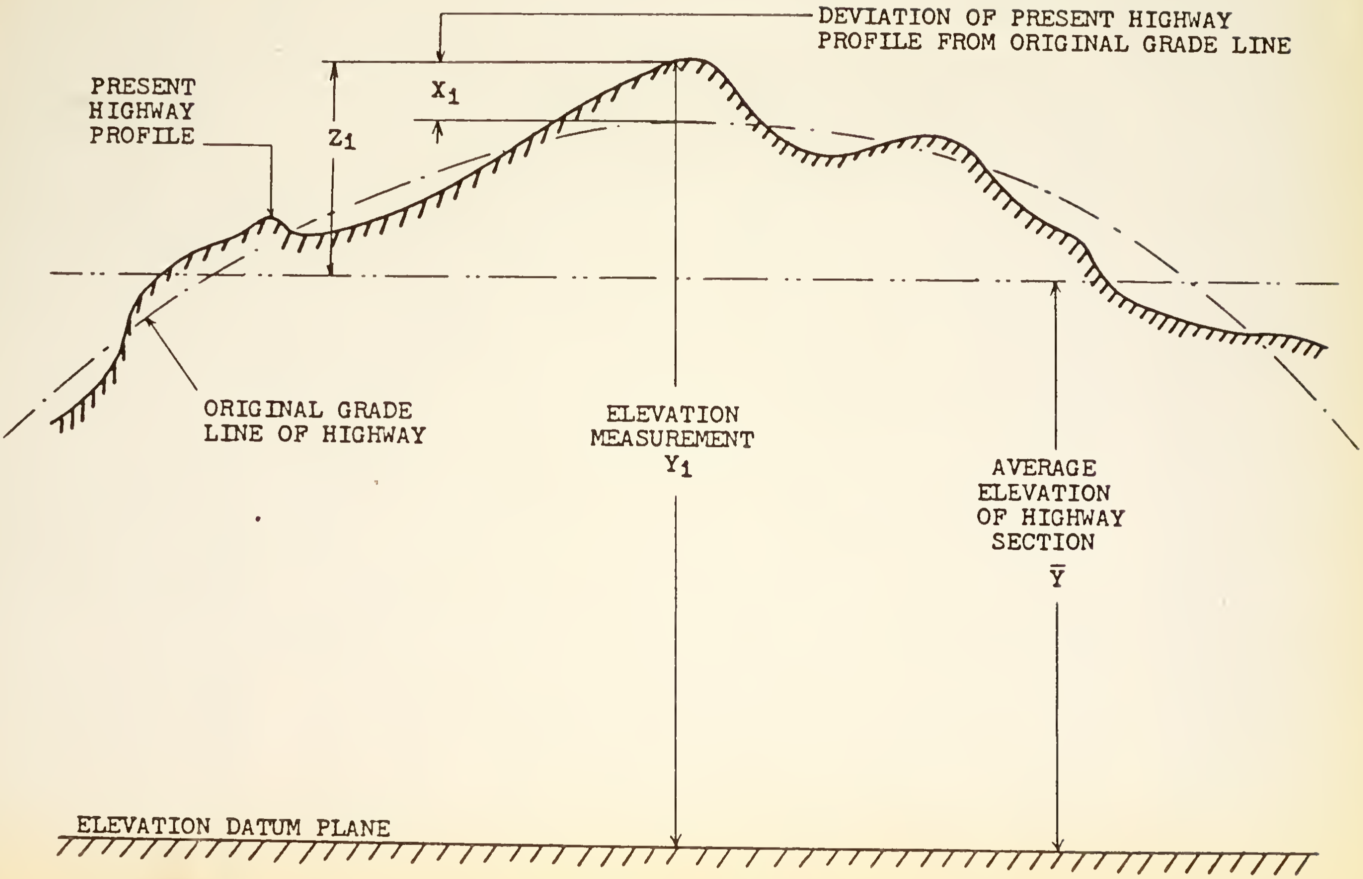


FIGURE 1 RELATIONSHIP BETWEEN ELEVATION MEASUREMENTS AND HIGHWAY DEVIATIONS

original grade line must be obtained. A fundamental problem is therefore that of selecting a procedure for obtaining these deviations. It is these deviations that are introduced into the calculation of a power spectrum in order to obtain a suitable criterion of the condition of the pavement.

Unfortunately no convenient reference is usually available to measure the deviation of the present highway profile from the original grade line, and as a consequence certain mathematical techniques must be employed to obtain the desired deviations. Since the original grade line is not accurately known, it is therefore difficult to be certain that a selected mathematical procedure will yield the correct results. Furthermore, if different mathematical procedures are used, then different power spectra will result. As a consequence, it is therefore possible to obtain different power spectra from the same set of elevation measurements, depending on how the deviations were obtained from the elevation measurements of the highway profile. The fundamental problem is therefore that of starting with the present elevation measurements indicated by Y_i and of obtaining the deviation of the present highway profile from the original grade line as indicated by X_i. The values of X_i are then used to calculate the desired elevation power spectrum.

One technique in common use for obtaining the desired deviations consists of first obtaining the average elevation $\overline{Y}$ from the entire set of elevation measurements Y_i. This value is then subtracted from each

elevation measurement in turn to obtain the values indicated by Z_i. A running mean, established by a selected number of these quantities, is then subtracted from the value of Z_i at the midpoint of this mean to obtain the deviation X_i shown in Figure 1. The values of X_i are then used to calculate the power spectrum. One problem that is immediately encountered is that of selecting an appropriate number of values to form the running mean. If this number is relatively small then longer wavelengths are virtually excluded from the calculation. The question thus arises as to the wavelengths that must be retained in calculating a power spectrum. Previous research (4) indicates that the use of this technique introduces an amplification of certain wavelengths that may be present in the highway profile. If a long running mean is established using a large number of values of Z_i, then large deviations will be obtained. If the running mean is very short, then much smaller deviations will be obtained. Since the magnitudes of these deviations will directly influence the elevation power spectrum, a consistent approach to the problem of determining the appropriate length of a running mean is necessary.

Another method for obtaining deviations is to approximate the original grade line by passing a second order least squares curve through the existing elevation measurements. Deviations are then obtained between this curve and the existing elevation measurements to procure the values X_i shown in Figure 1. These values are then used to calculate the elevation power spectrum.

Virtually the same question can be asked concerning this method that was encountered in the case of the running mean. The selection of an appropriate number of elevation measurements to be used in forming this second order base line is not easy to answer. In general, a second order curve will afford a reasonable approximation to the original grade line of a well designed highway if it is of appropriate length. If, however, the grade line of the highway contains a point of inflection then a second order approximation will not be accurate and the resulting deviations will be much larger than they should be. A short length of base line approximated in this fashion will largely remove the effect of long wavelengths while a long approximation to the base line will retain the longer wavelengths in the profile. The filtering characteristics of the second order base line are superior to those of the running mean in that they do not give excessive amplification to certain wavelengths in the pavement profile. A major difficulty encountered with the use of the second order base line is due to the fact that successive sections of these base lines have discontinuities at the ends of the sections and these influence the power spectrum calculations.

Another technique (5) that has been employed for the purpose of obtaining deviations is that of using successive differences between adjoining elevation measurements. When this technique is employed it is necessary to make an appropriate correction in the resulting elevation power spectrum in order to remove the pronounced filtering effect that is introduced.

The problem of obtaining deviations from the existing profile to the original grade line is difficult, and no completely satisfactory technique for doing this is at present available. Since this constitutes an important step in the calculation of an elevation power spectrum it is desirable that a suitable procedure for accomplishing this task be developed.

C. Procedure for Calculating Power Spectrum After Elevation Deviations Have Been Obtained

The procedure used for calculating the elevation power spectra is that developed by Blackman and Tukey (6) and is summarized as follows.

After the elevation deviations have been obtained the mean lagged products are calculated using the following relationship:

$$C_r = \frac{1}{n - r} \sum_{q=o}^{q=n-r} X_q \cdot X_{q+r}$$

C_r = sample autocovariance at lag value $r(\Delta\tau)$

r = lag index (0, 1, 2, --- m)

n = number of deviation measurements minus one

X_q = elevation deviation at station q

q = deviation index (0, 1, 2, --- n)

If this relationship, sometimes referred to as the autocovariance function, is plotted as a function of lag index h it should approach zero as the lag index increases. Hopefully this function would go to zero for some value of the lag index and remain at zero for any greater value of the index. Unfortunately this is not the case with highway data, and hence it is necessary to select some lag index h at which the function will be terminated. This involves the selection of a maximum lag value to be used in the analysis, and in this case a maximum lag value of fifty was used. In passing it should be noted that the zero lag value of the autocovariance function gives the mean square value of the elevation deviations and these values should check with the area under the resulting power spectrum curve.

The next step is to calculate the raw spectral density estimates using the relationship:

$$V_h = 2\Delta\tau\left[C_o + 2 \sum_{r=1}^{r=m-1} C_r \cos\left(\frac{hr\pi}{m}\right) + C_m \cos(h\pi) \right]$$

$\Delta\tau$ = distance between elevation measurements (taken to be one foot)

m = maximum lag index

h = frequency index (0, 1, 2, - - - m)

V_h = raw spectral density estimate at frequency index h

This relationship provides the Fourier transformation of the autocovariance function that is an essential process of this calculation.

The final step is to compute the refined spectral density estimates using the relationship:

$$U_h = 0.23 \ V_{h-1} + 0.54 \ V_h + 0.23 \ V_{h+1}$$

U_h = refined spectral density estimate at frequency index h

(For further information consult reference (6).)

These values are the ordinates of the elevation power spectrum curve and have the units of feet squared per cycle per foot. The abscissa have units of cycles per foot, and the resulting area under the power spectrum curve is thus the product of these two quantities which is feet squared.

Other investigators (5) have introduced an additional step in which the filtering effect of the technique used to obtain the elevation deviations is removed from the power spectrum. A previous study was conducted of these filtering techniques. The conclusion of this investigation (4) was that in general, for the filtering procedures employed, the additional calculations did not appreciably modify resulting power spectra. Because of the greatly increased cost of computation in carrying out these additional filtering operations they were not introduced in this investigation.

The relatively minor effect on the values obtained would not appreciably change the results that were obtained in this study.

As can be seen in Figure 2, the ordinates of the power spectrum in the first frequency band are extremely large, and as a consequence the area associated with this part of the curve is also large. Furthermore, the greatest effect of the filtering procedure is to modify the ordinates of the power spectrum curve in this range. As a consequence, areas under the power spectrum curves were calculated with and without this first frequency band. These areas gave the mean square value of the roughness of the highway and were used as criteria of pavement condition.

The most important decision to be made in calculating power spectra is that of selecting the procedure for obtaining the elevation deviations. The results that were obtained were therefore influence to a much larger extent by the decision concerning the preliminary data processing procedure used to obtain the elevation deviations rather than by decisions concerning the procedure for calculating the power spectrum after these deviations had been obtained. For this reason a more extensive discussion of the mathematical procedure for calculating the power spectrum is not included.

D. Criteria of Accuracy for Power Spectra

Many devices for evaluating pavement condition give a single number that can be used for this purpose. In order to compare the results

obtained from a power spectrum calculation it is therefore necessary to obtain a single number that will be comparable to the other criteria that are considered for this purpose. A criterion of roughness, based on the elevation power spectrum calculation was therefore taken to be the area under the power spectrum curve. This number was then compared to other criteria of pavement condition. In this report the most convenient criterion of pavement condition was that obtained from the Bureau of Public Roads roughometer, and in all cases the results of the power spectrum calculations are compared with this criterion.

Although it is possible to obtain a single number to represent the pavement condition from the power spectrum calculation (area under the power spectrum curve), it is desirable to make a more detailed comparison of the highway power spectrum.

It is possible to do this if the nature of the highway profile can be deduced from the behavior of the vehicle travelling over the highway. A calculation of this type has been made in which the condition of the highway has been determined from dynamic tire pressure measurements. With this information it is possible to compare an elevation power spectrum obtained by observing the behavior of a vehicle. This type of comparison enables an investigator to see where large differences may exist between the two power spectra.

Two criteria are thus available by which an elevation power spectrum can be judged. One is the area under the power spectrum

curve that can be compared with any measurement of pavement condition that can be represented as a single number. The other criterion is a comparison of the computed elevation power spectrum with one obtained by observing vehicle behavior.

III. DISCUSSION OF RESULTS

A. Typical Elevation Power Spectra

During this investigation elevation power spectra were calculated for fifteen different sections of highway. For each section at least two different preliminary data processing procedures were employed, and in many cases additional procedures were also used. As a consequence, there are several elevation power spectra for each test section and space does not permit all of these curves to be included in this report. As a consequence, therefore, those power spectra that are considered typical are included.

Typical elevation power spectra are shown in Figures 2, 3, and 4. In Figure 2 the elevation power spectra are shown for highway test section Number 45 which was a rigid pavement having a BPR roughometer rating of 116 inches per mile. The dotted curve shown in this figure is the power spectrum obtained by calculating deviations using the least squares second order base line through three hundred elevation values. Since the approximate length of this test section was 1200 feet, approximately four such base lines were used in making this calculation. The deviations from each of the base lines were grouped together and the resulting power spectrum calculation was made from these data.

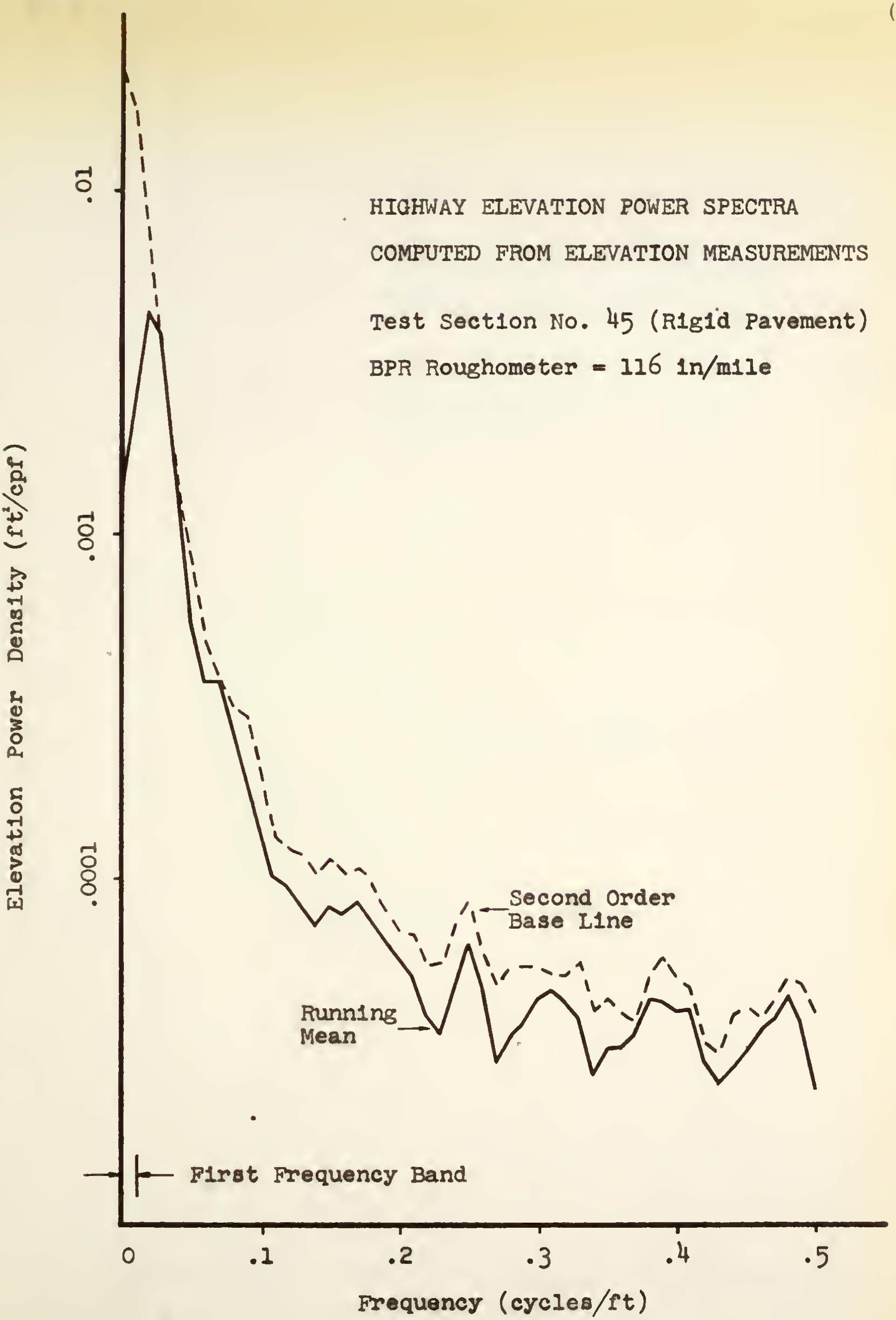

HIGHWAY ELEVATION POWER SPECTRA
COMPUTED FROM ELEVATION MEASUREMENTS
Test Section No. 45 (Rigid Pavement)
BPR Roughometer = 116 in/mile
Second Order Base Line
Running Mean
First Frequency Band
Elevation Power Density (ft^2/cpf)
.01
.001
.0001
0
.1
.2
.3
.4
.5
Frequency (cycles/ft)

FIGURE (2)

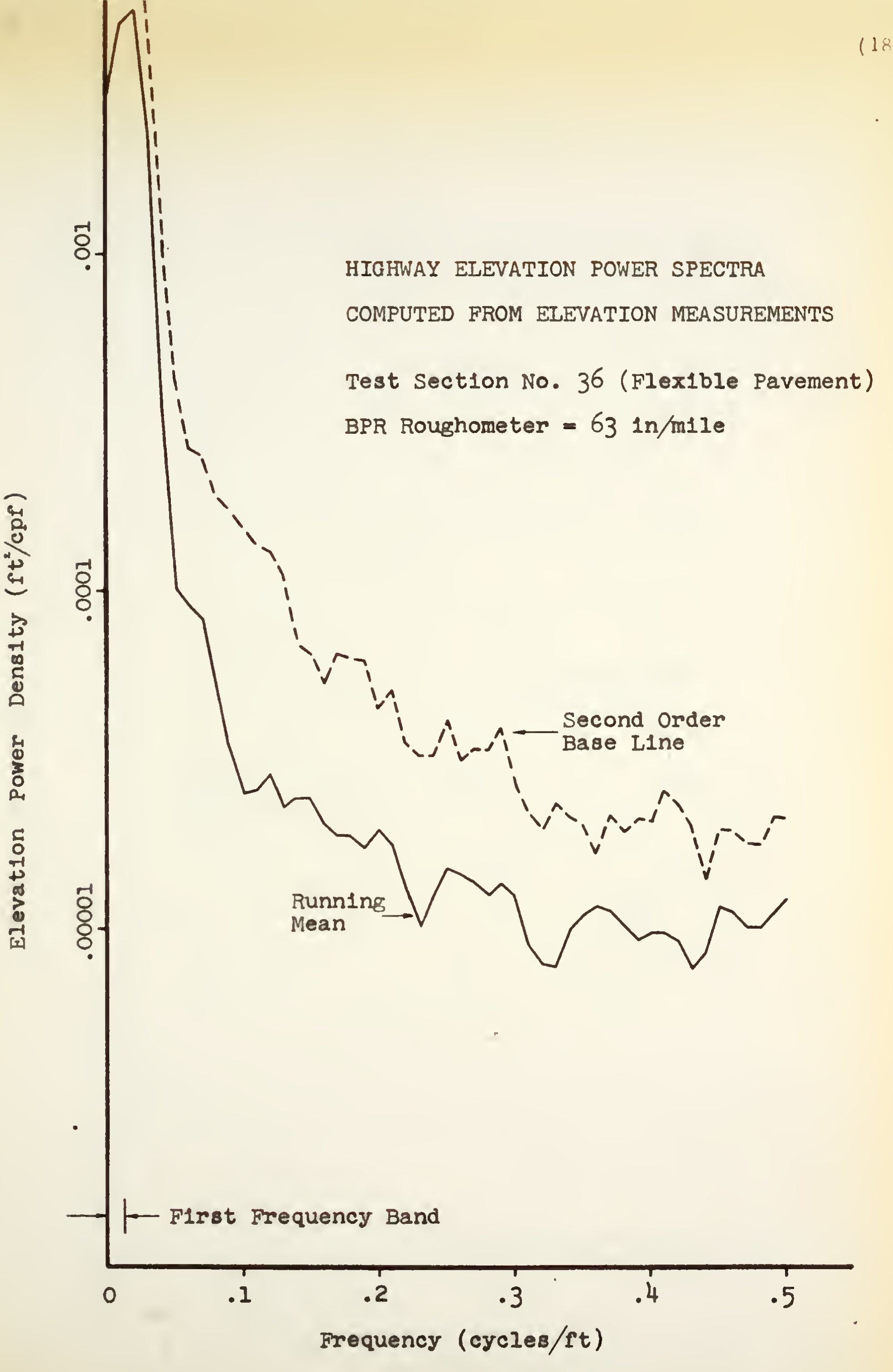

HIGHWAY ELEVATION POWER SPECTRA
COMPUTED FROM ELEVATION MEASUREMENTS
Test Section No. 36 (Flexible Pavement)
BPR Roughometer = 63 in/mile
Second Order Base Line
Running Mean
First Frequency Band
Elevation Power Density (ft²/cpf)
.001
.0001
.00001
0
.1
.2
.3
.4
.5
Frequency (cycles/ft)

FIGURE (3)

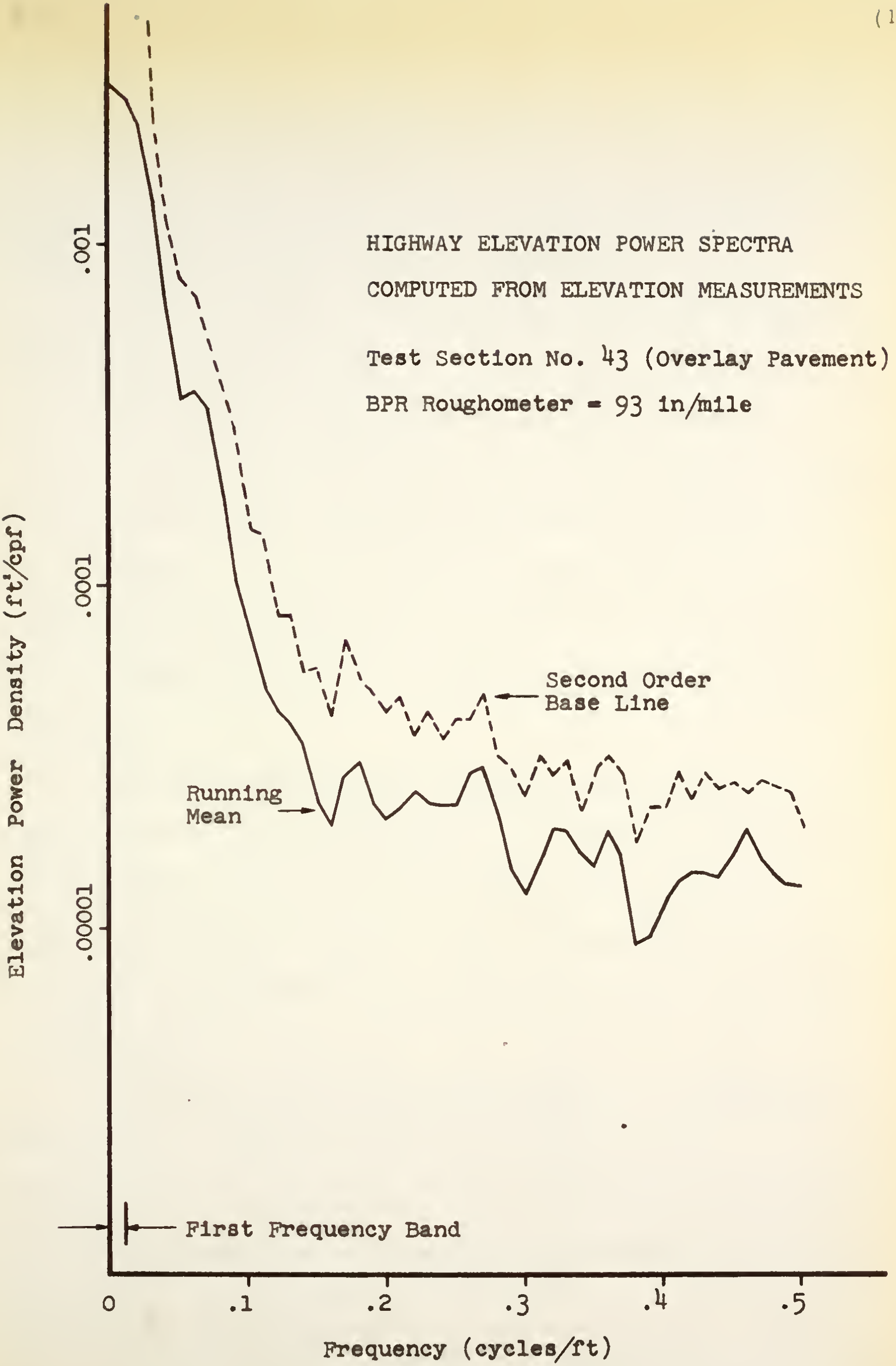

HIGHWAY ELEVATION POWER SPECTRA
COMPUTED FROM ELEVATION MEASUREMENTS
Test Section No. 43 (Overlay Pavement)
BPR Roughometer = 93 in/mile
Second Order Base Line
Running Mean
First Frequency Band
Elevation Power Density (ft²/cpf)
.001
.0001
.00001
0
.1
.2
.3
.4
.5
Frequency (cycles/ft)

FIGURE (4)

The solid curve indicates the resulting elevation power spectrum when deviations are obtained from the same elevation measurements using a fifty-one foot running mean as previously described.

Although these curves appear reasonably close together there is a very large numerical difference in the low frequency region of the curves. Since wavelength is the reciprocal of frequency, this large difference occurs at very long wavelengths. Both curves indicate, however, that the long wavelengths, associated with low frequencies, predominate as far as amplitude is concerned. In addition, both curves indicate a reasonably constant value for frequencies between .2 to .5 cycles per foot. (This region corresponds to wavelengths ranging from five to two feet in length.)

The effect of the technique employed to obtain the deviations is clearly shown in this figure. The running mean very effectively filters out long wavelengths, while these same wavelengths are retained when the second order base line is employed. In general this is true for all highways, and the curves shown in Figure 2 are typical of those obtained from other test sections.

A convenient criterion of pavement condition can be obtained by measuring the area under the respective power spectrum curves. Using this criterion Figure 2 indicates that a larger value would be obtained for the second order base line than for the power spectrum computed from the running mean.

At this point it is appropriate to recognize that such a criterion will depend to a large extent upon the preliminary data processing procedure employed, and that the largest contribution to the area under the power spectrum curve occurs in the very low frequency region. Since the elevation power spectrum calculation is made by frequency bands, it has been the practice of some investigators to omit the area under the power spectrum curve that occurs in the first frequency band. This would partly eliminate the large difference resulting from the two different methods of obtaining elevation deviations as well as avoiding other complications. In subsequent results the consequences of omitting this portion of the area under the power spectrum curve are discussed in greater detail.

The results obtained for a flexible pavement are shown in Figure 3 in which the pavement had a BPR roughometer rating of 63 inches per mile.

Again a large difference in ordinates is indicated in the low frequency region, but in addition, a greater difference exists between the two curves in the higher frequency region that existed for the curves shown in Figure 2. These results are typical for calculations made on flexible pavements. It is shown in Figure 3 that the data processing procedure makes a greater difference in the resulting spectrum calculation than existed in Figure 2. This is typical for flexible pavements when a calculation based on a running mean is compared to the same calculation based on the use of a second order base line.

Power spectra calculated for a pavement of overlay construction having a BPR roughometer rating of 93 inches per mile are shown in Figure 4. At this point it is disturbing to note that the first ordinate in Figures 2, 3, and 4 is apparently unrelated to the roughometer ratings of the highway sections in question. This discrepancy is revealed in subsequent results.

In general, all elevation power spectrum curves have essentially the same shape. The largest ordinates occur at the smallest frequencies, indicating that long wavelengths in the highway have the greatest amounts of power associated with them. The minor fluctuations, evident in all curves, are not statistically significant. These curves are thus typical of practically all of the elevation power spectra that were computed.

B. Comparison of Elevation Power Spectra With BPR Roughometer Ratings

If the area under the elevation power spectrum is taken as a criterion of pavement condition, it can be compared directly with BPR roughometer ratings of the same pavement sections. This comparison is shown in Figures 5, 6, and 7. In each of these figures there are four curves. This is due to the fact that the related power spectra were calculated by using deviations from both a running mean and a least

MEAN SQUARE DEVIATION VERSUS BPR ROUGHOMETER RATING

(Rigid Pavements)

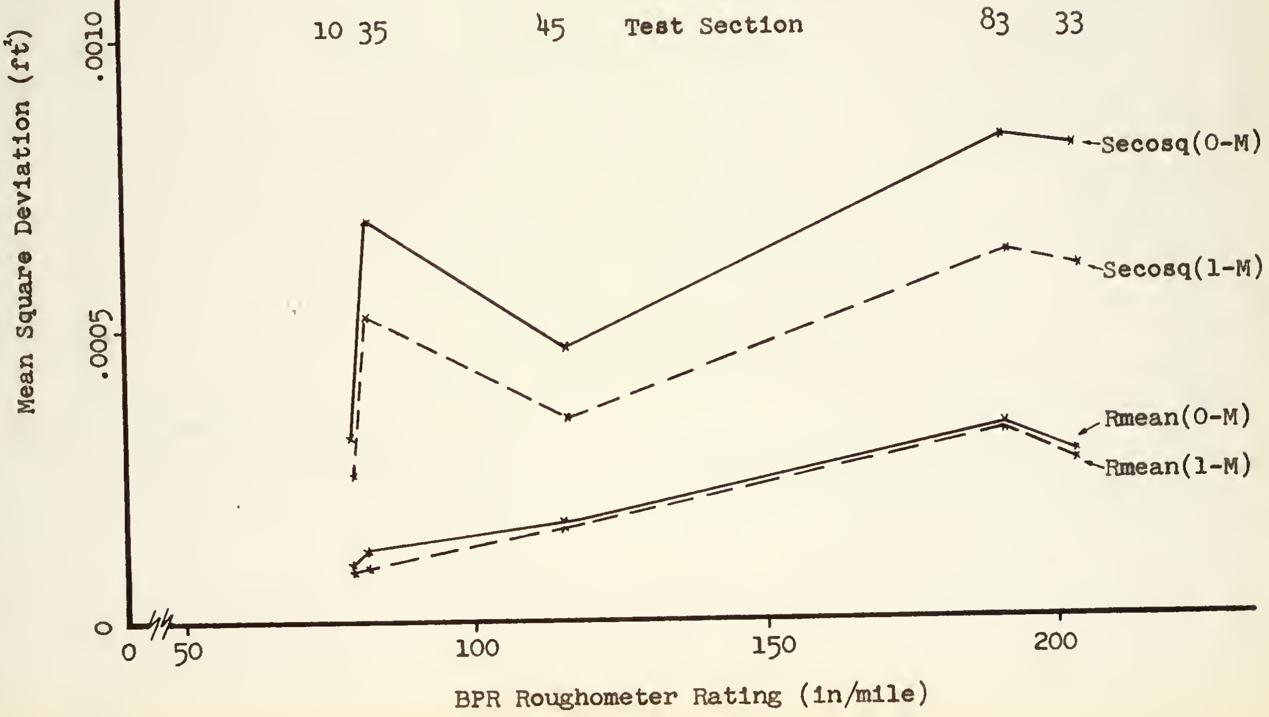
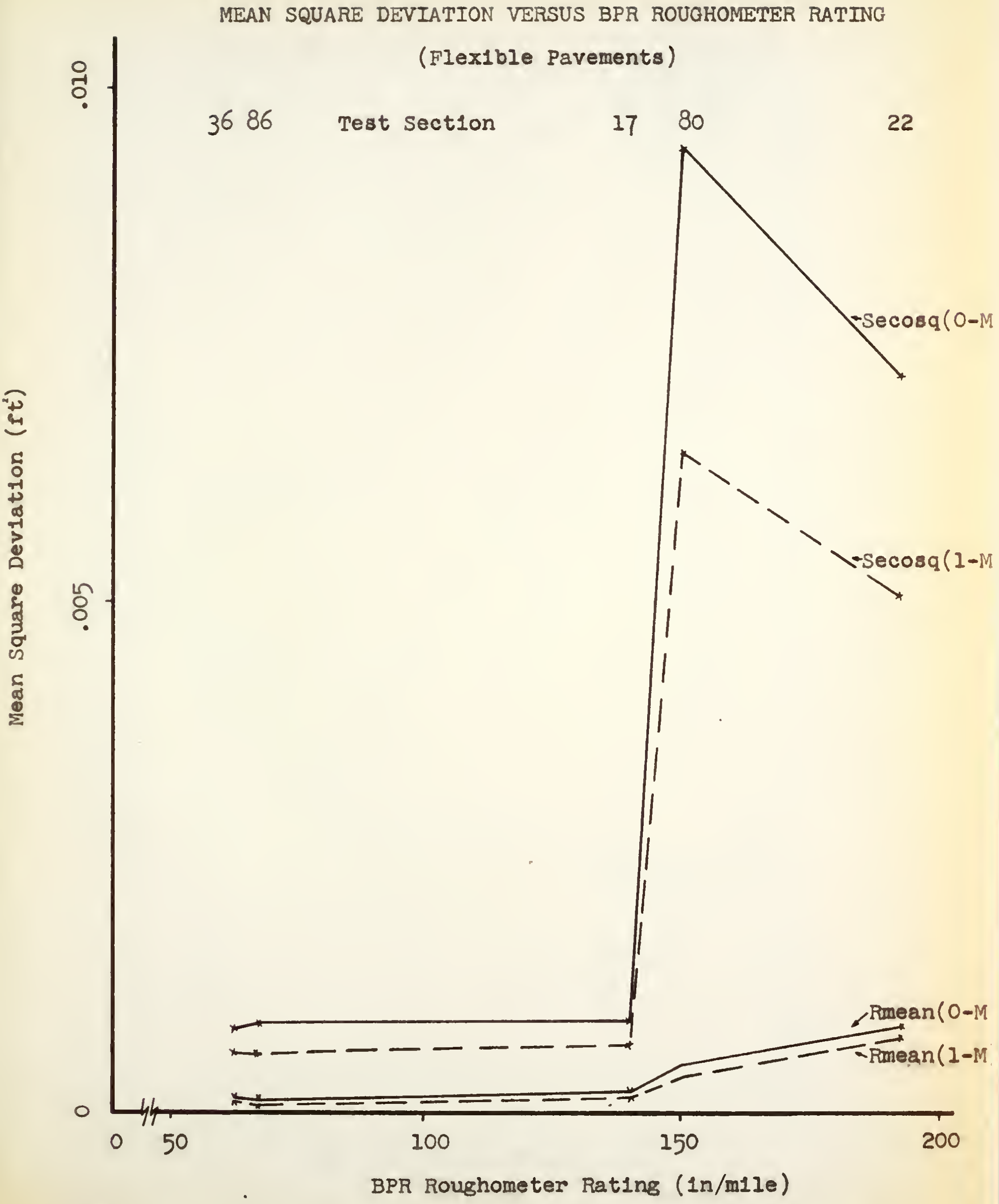


FIGURE (5)


MEAN SQUARE DEVIATION VERSUS BPR ROUGHOMETER RATING

(Flexible Pavements)

FIGURE (6)

MEAN SQUARE DEVIATION VERSUS BPR ROUGHOMETER RATING

(Overlay Pavements)

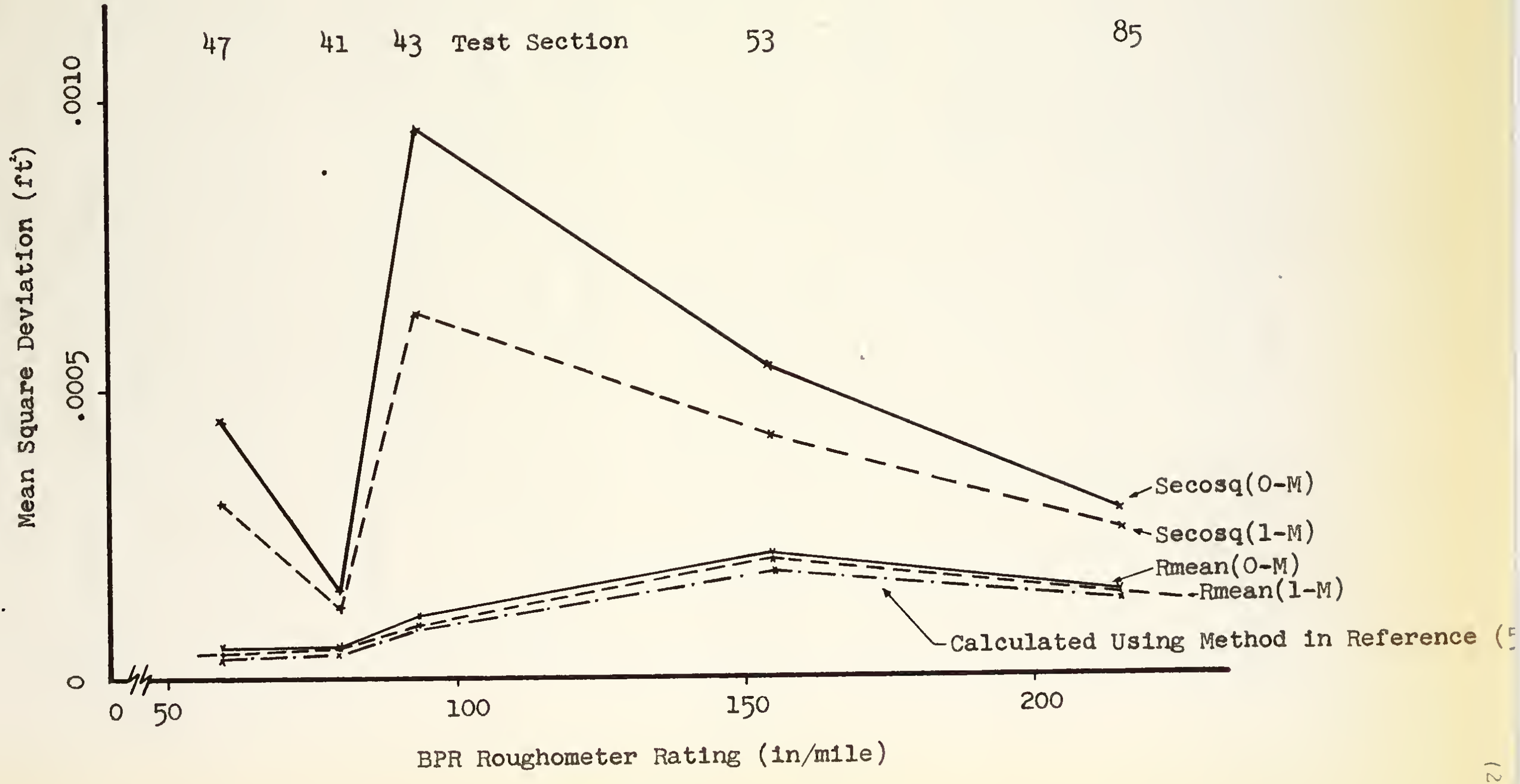


FIGURE (7)

squares second order base line. For each spectrum thus obtained, the area was determined with and without the first frequency band as previously discussed. The following legends therefore appear on the curves:

Rmean (O - M) = running mean (51 feet), total area computed
Rmean (1 - M) = running mean (51 feet), area due to first frequency band omitted
Secosq (O - M) = second order base line (300 feet), total area computed
Secosq (1 - M) = second order base line (300 feet), area due to first frequency band omitted

The results for rigid pavements are shown in Figure 5, in which the use of the running mean gives a better relationship with the BPR roughometer ratings than does the use of the second order base line. In addition, this figure indicates that omitting the effect of the first frequency band does not appreciably alter the relationship in either case.

In Figure 6 the results are shown for five flexible pavements. Here a much less satisfactory relationship is indicated. Again the use of the running mean produces a more reasonable relationship than that obtained from the second order base line, and the effect of using only

part of the area under the power spectrum curves is again shown to have little influence on the relationship between the two criteria of pavement condition in question.

A comparison of the same relationship for five pavements of overlay construction is shown in Figure 7. Again better results are obtained when a running mean is used, but unfortunately a relationship comparable to that observed in Figure 5 is not revealed.

The curves shown in Figures 5, 6, and 7 indicate that the use of a running mean provides a more reliable criterion of pavement condition than does the use of the second order base line. Unfortunately even this criterion is not completely reliable, and pavements that are extremely rough do not exhibit a corresponding increase in the area under their power spectrum curves.

The relationship between the area under the power spectrum curve and the BPR roughometer rating is influenced by the technique for calculating the power spectrum as shown by Figures 5, 6, and 7.

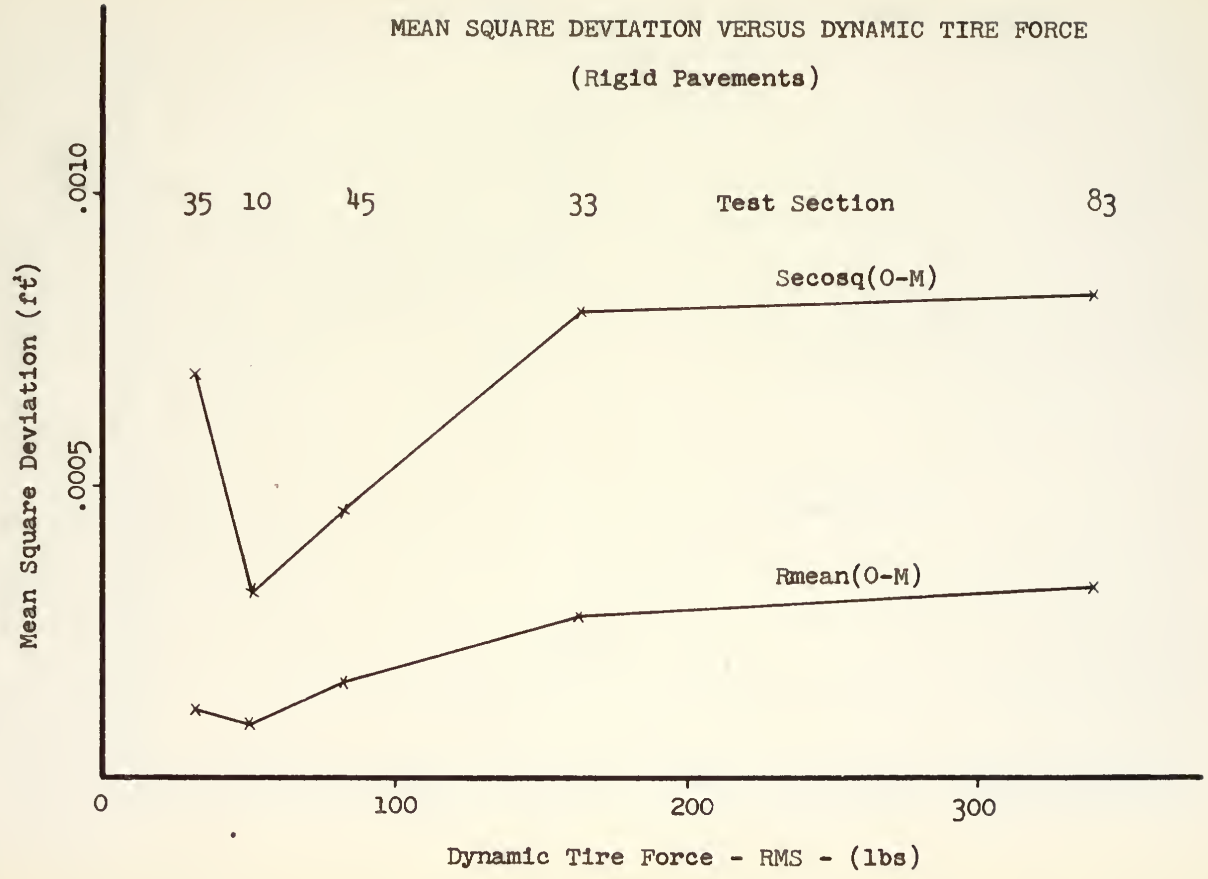
This relationship was also investigated by using another technique for calculating the power spectrum in which a different procedure was employed (5) to determine the deviations, and a slightly different method was used to make the remaining calculations. The results of this study are shown in Figure 7, in which a comparison is made with the previous relationships. This comparison indicates that almost identical results are obtained when using either method for calculating the power spectra.

Neither method indicates that the roughest pavement (by BPR roughometer measurements) has the largest area under the power spectrum curve. Although other portions of the curves appear reasonable, the failure of both methods to indicate the greater roughness of the pavement in question is somewhat disturbing.

C. Comparison of Elevation Power Spectra With Measured Dynamic Tire Force

In a previous article (7) a reasonably good relationship was observed between the dynamic tire force and the BPR roughometer ratings. It was therefore considered of interest to plot the area under the power spectrum curves against the mean square value of the dynamic tire forces measured on the highway sections in question. The results are shown in Figures 8, 9 and 10. In Figure 8, additional roughness is reflected in the dynamic tire force, but for the roughest pavement the area under the power spectrum curve is again not proportionately larger. The best results were obtained for the flexible pavements, Figure 9, but for the overlays the results were less satisfactory.

Again, the running mean gives better results, but there are pavements that are rougher (considering dynamic tire forces) for which the spectrum criterion indicates a contrary condition.


MEAN SQUARE DEVIATION VERSUS DYNAMIC TIRE FORCE

(Rigid Pavements)

FIGURE (8)

MEAN SQUARE DEVIATION VERSUS DYNAMIC TIRE FORCE

(Flexible Pavements)

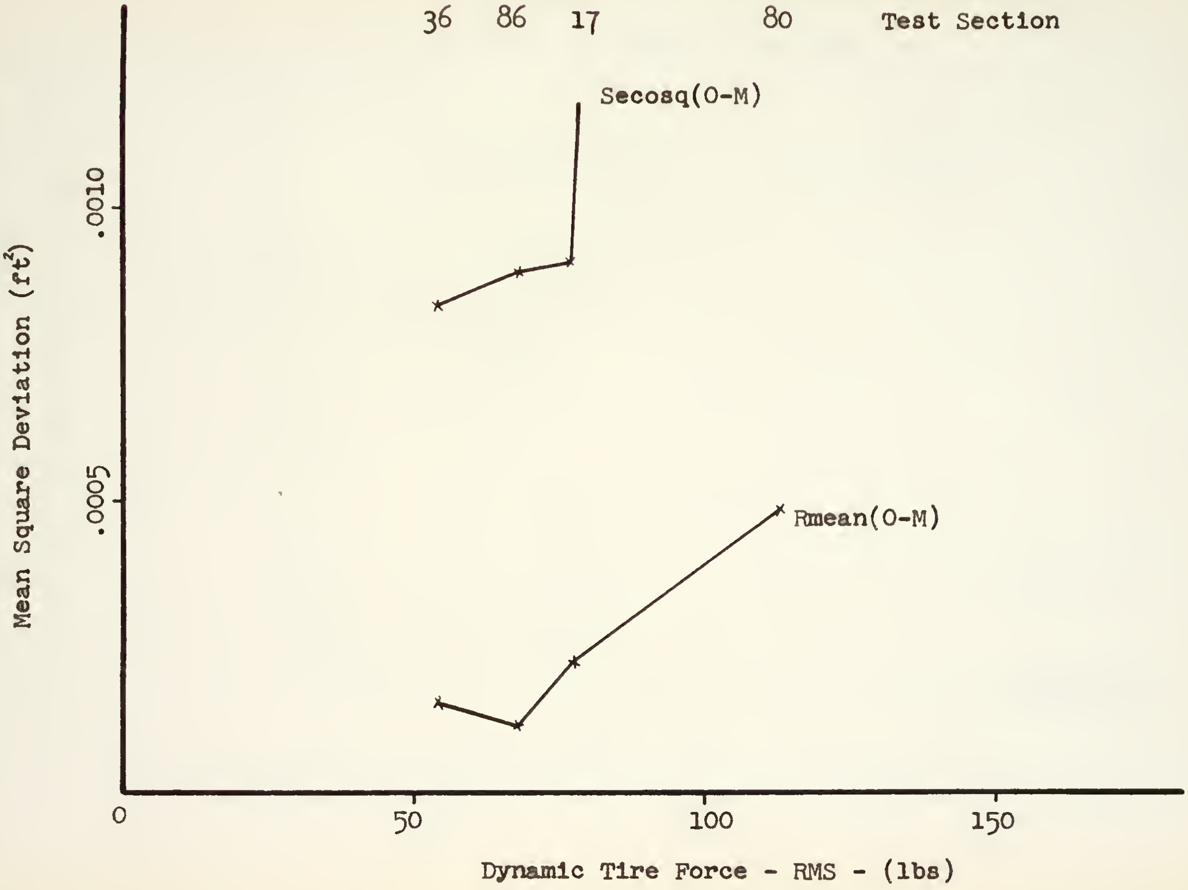


FIGURE (9)

MEAN SQUARE DEVIATION VERSUS DYNAMIC TIRE FORCE

(Overlay Pavements)

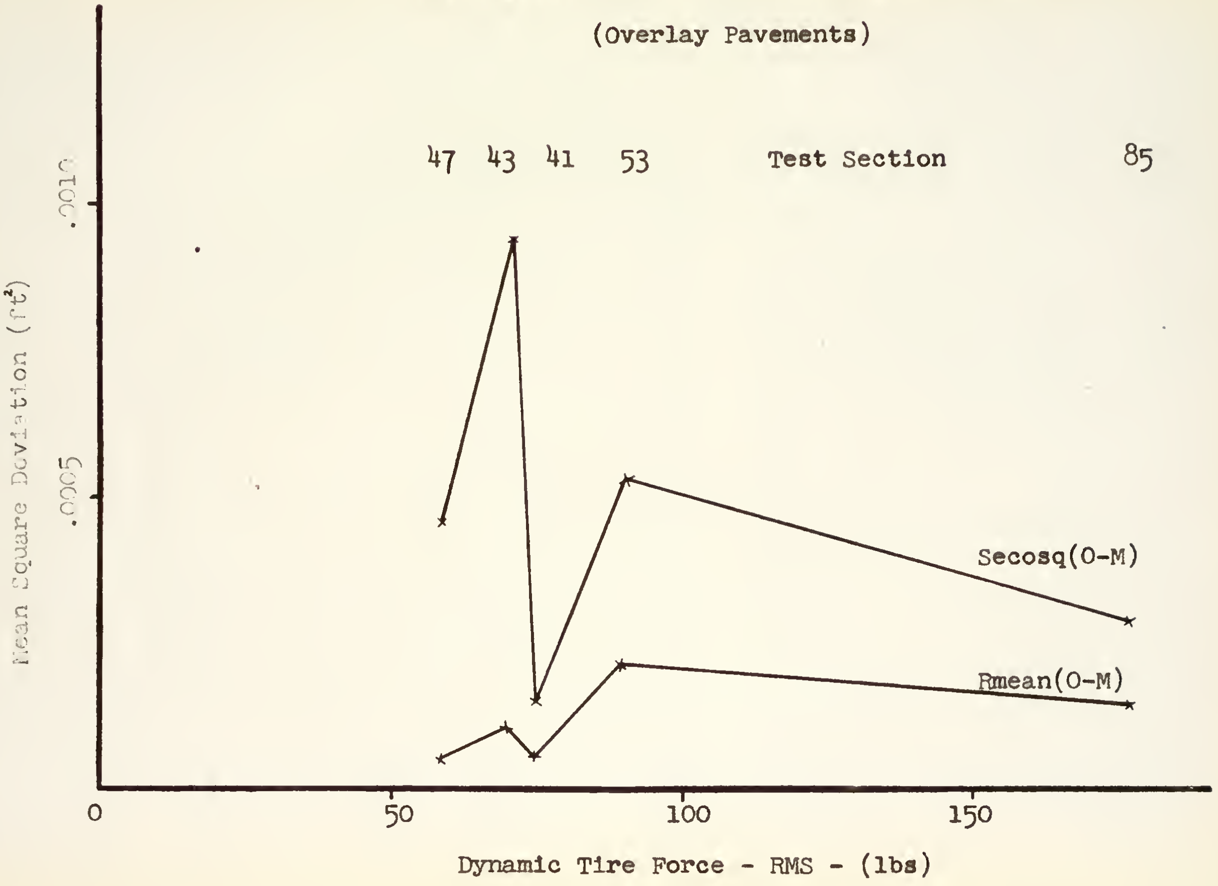


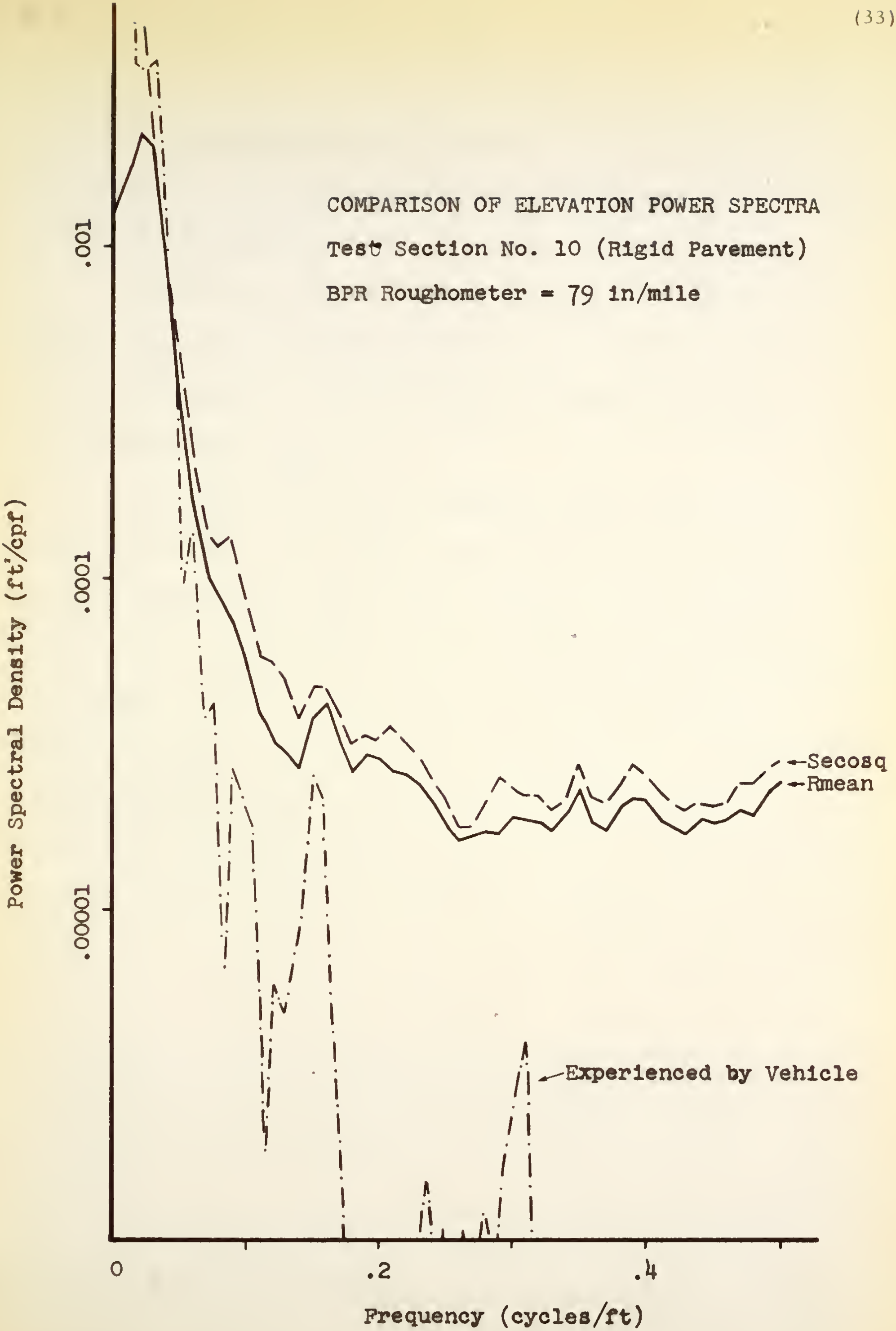
FIGURE (10)

D. Comparison of Elevation Power Spectra with the Power Spectra Experienced by the Vehicle

The evidence presented so far indicates that the use of the running mean is preferable to the second order base line when calculating elevation power spectra. This conclusion appears to be valid when criteria of pavement condition are compared. If, however, the elevation power spectra are to be used to predict vehicle behavior, the question arises as to the validity of either of these methods for this purpose.

In a recent paper (8) the elevation power spectrum experienced by a vehicle was presented. It is interesting to compare an elevation power spectrum based upon experimental vehicle behavior with the spectra obtained from the elevation measurements. A comparison of this type is shown in Figure 11, in which the elevation power spectrum experienced by a vehicle moving over a highway at a constant velocity is shown by the dash lines. This figure indicates that both techniques for calculating elevation power spectra from elevation power measurements indicate more power (larger amplitudes) in the highway for the shorter wavelengths than is actually experienced by the vehicle.

Moreover, both methods underestimate the power in the long wavelengths (low frequencies) as compared to that experienced by the vehicle. In this region, however, the use of a second order curve gives



COMPARISON OF ELEVATION POWER SPECTRA

Test Section No. 10 (Rigid Pavement)

BPR Roughometer = 79 in/mile

FIGURE (11)

a more accurate estimate of power than does the use of the running mean. Since the power in this region is much larger than the power in other regions, this is an important point in favor of the use of a second order curve.

Neither a running mean nor a second order base line provides deviations that yield a completely satisfactory power spectrum for characterizing a highway, and both techniques overestimate the power in the high frequency region.

Unfortunately this is not a negligible situation as far as the dynamic tire forces are concerned. This is due to the fact that the vehicle is extremely sensitive to highway excitation at high frequencies, and as a consequence dynamic tire forces predicted from elevation power spectra shown in Figure 11 will be greater than the forces actually measured when the vehicle is operated over the highway. The comparison indicated in this figure reveals the fact that neither method for calculating an elevation power spectrum from elevation measurements is entirely satisfactory as far as the prediction of vehicle forces is concerned.

E. Comparison of Highway Power Spectra Computed from Elevation Measurements with the Power Spectrum Computed from Data Obtained Using Special Devices

During this investigation a truck mounted profilometer (9) operated by the University of Michigan, and a special test vehicle (10)

operated by the General Motors Corporation, were utilized on the test sections under consideration. Information from these devices was available in the form of oscillograph records. The labor involved in reading these records in order to obtain data for calculating power spectra was appreciable, and as a result only a limited amount of such data could be obtained.

Actually the data obtained from the oscillograph records could not be used directly to calculate the power spectra. It was necessary to preprocess these data in order to insure a zero mean value, and thus individual judgment was involved in selecting the preprocessing procedure. In addition, the selected procedure influenced the resulting power spectrum, and thus the curves that follow do not represent exclusively the characteristics of the instruments used to collect the data. In view of this situation it is therefore not possible to make a detailed comparison of the instruments involved in these tests.

The truck mounted profilometer has been described in previous reports and will not be dealt with extensively here. It is sufficient to say that this device obtains deviations of the highway profile from a base line established by the profilometer. From this information it was possible to calculate an elevation power spectrum after the data had been processed to obtain a zero mean value and the results of this calculation are shown in Figure 12. A comparison is made with the elevation power spectrum

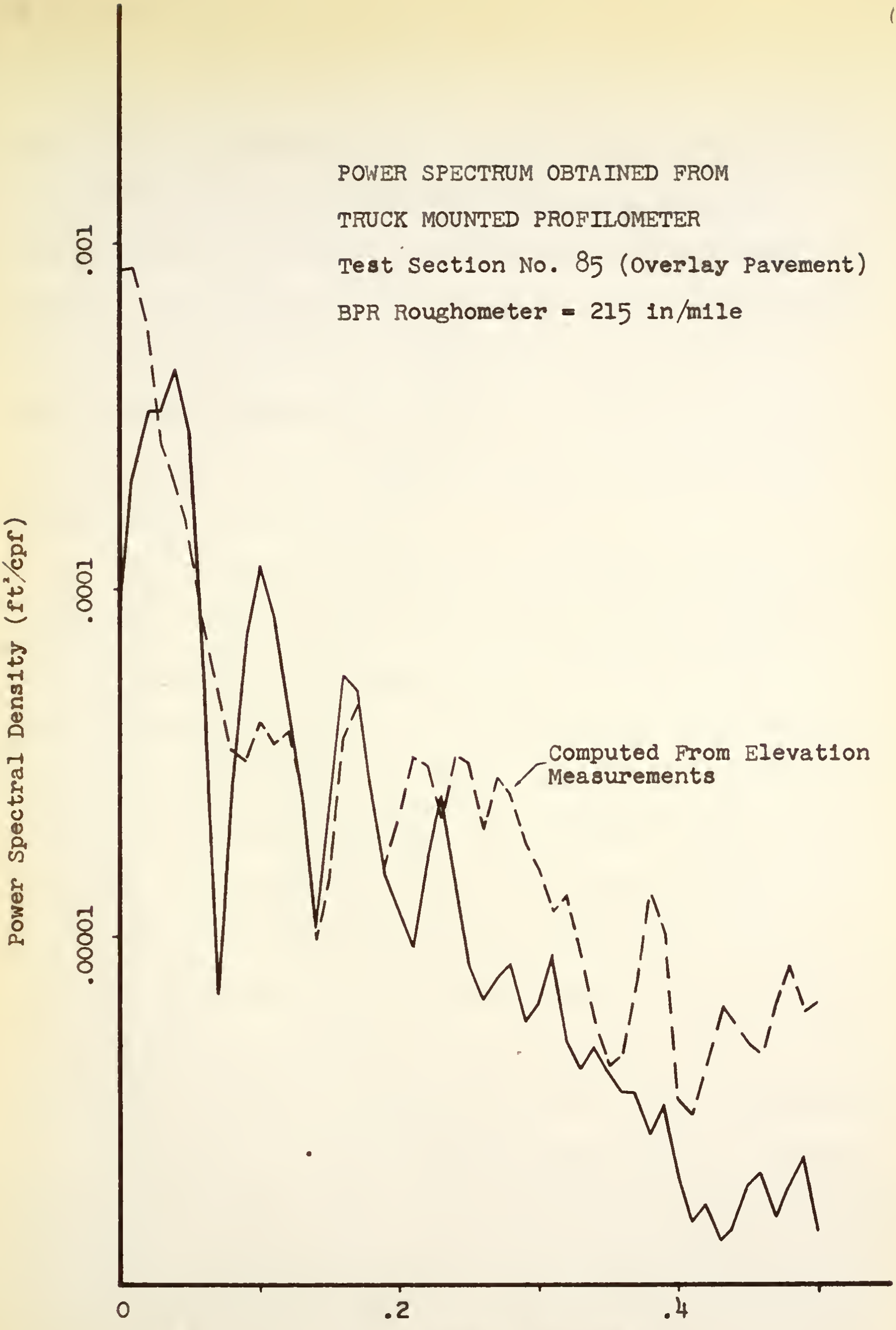

POWER SPECTRUM OBTAINED FROM
TRUCK MOUNTED PROFILOMETER
Test Section No. 85 (Overlay Pavement)
BPR Roughometer = 215 in/mile
Computed From Elevation Measurements
Power Spectral Density (ft²/cpf)
.001
.0001
.00001
0
.2
.4
Frequency (cycles/ft)

FIGURE (12)

computed from elevation measurements using the second order base line and this curve is shown by the dotted line in Figure 12. It is interesting to note that this device indicates less power in the high frequency region than does the power spectrum obtained from elevation measurements and for this reason gives a better approximation to the power spectrum experienced by the vehicle. It should be emphasized, however, that the information shown in Figure 12 is based on a very limited number of data values.

A specially instrumented truck, operated by the General Motors Corporation, utilized a servo-seismic electronic system to obtain elevation measurements of the highway profile. As in the case of the digital calculations, it was necessary to filter out the enormous wavelengths of the profile under consideration. This was done electronically, and provision was made to select the wavelengths that could be eliminated by the use of appropriate filters. The results obtained from this equipment thus depended upon the filter that was used to obtain the data. Moreover, in calculating a power spectrum from these data it was necessary to preprocess the data before making the power spectrum calculations, and this operation influenced the power spectrum calculated from these data.

In Figure 13 is shown an elevation power spectrum, calculated from data obtained by the servo - seismic system using a 90 foot electronic filter. Also shown in this figure is the elevation power spectrum calculated from the elevation measurements using a second order base line to obtain

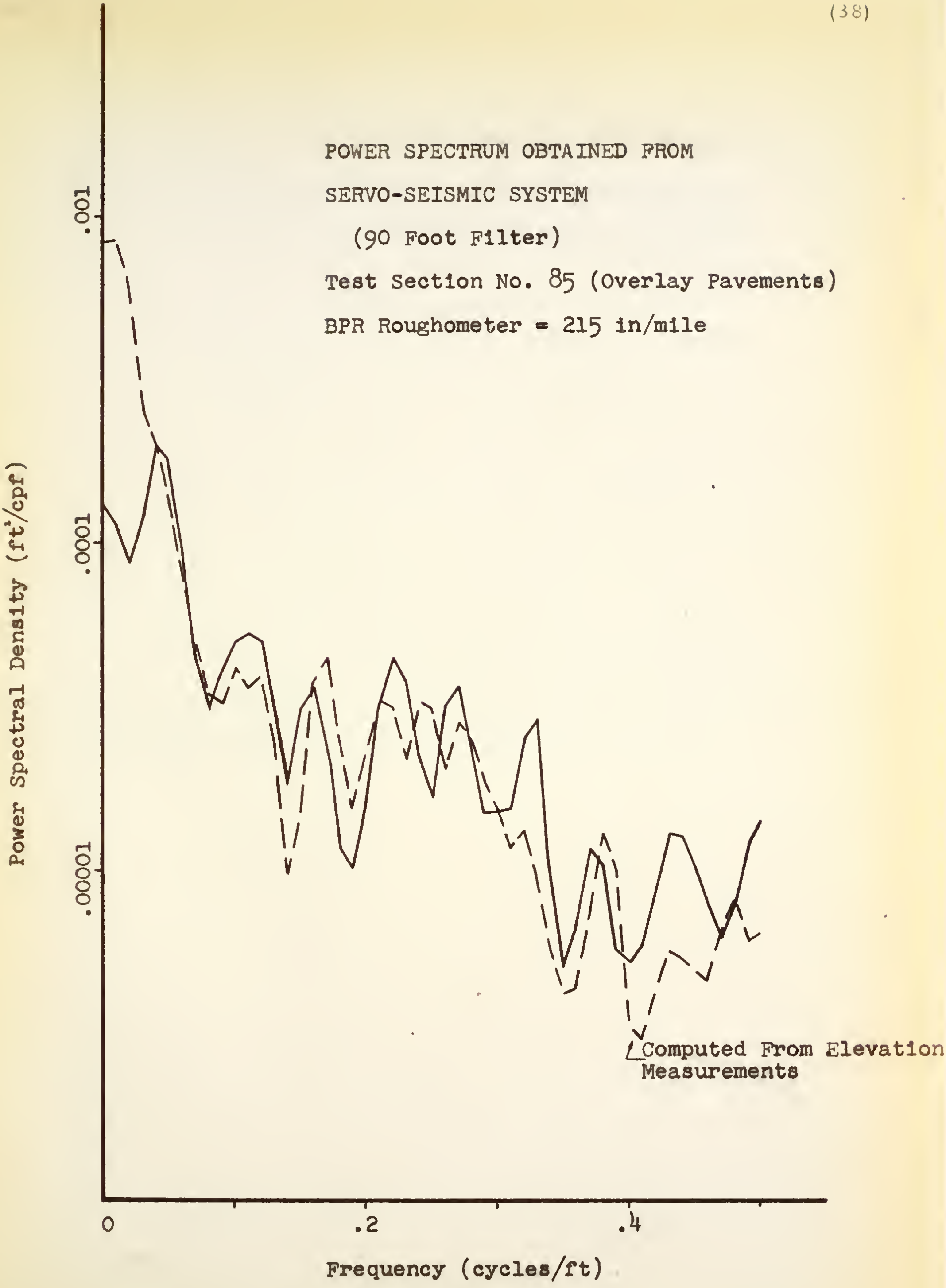

POWER SPECTRUM OBTAINED FROM
SERVO-SEISMIC SYSTEM
(90 Foot Filter)
Test Section No. 85 (Overlay Pavements)
BPR Roughometer = 215 in/mile
Computed From Elevation Measurements
Power Spectral Density (ft²/cpf)
.001
.0001
.00001
0
.2
.4
Frequency (cycles/ft)

FIGURE (13)

the elevation deviations. As would be expected, the power associated with the spectrum obtained using the servo-seismic device is less than the power associated with the curve obtained from the elevation measurements.

The effect of using a 600 foot filter in the servo-seismic device is shown in Figure 14. Here the same preliminary data processing technique was used on the data obtained from the General Motors device as was used on the elevation measurements. Although the comparison is favorable it cannot be considered significant because of the very limited number of data values that were used.

It should again be emphasized that the information shown in Figures 12, 13, and 14 is based on a very limited amount of data due to the fact that oscillograph records had to be processed by hand.

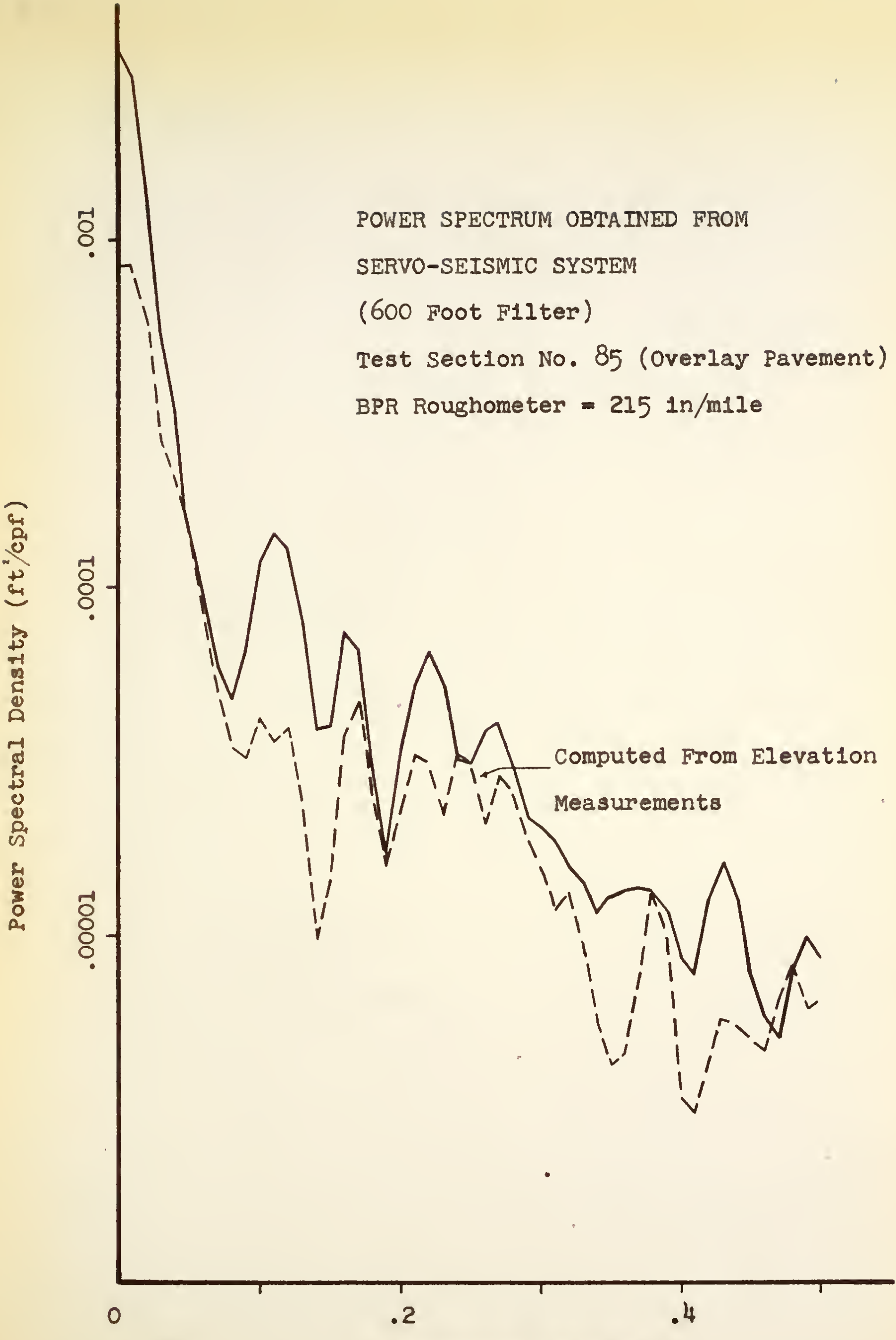

POWER SPECTRUM OBTAINED FROM
SERVO-SEISMIC SYSTEM
(600 Foot Filter)
Test Section No. 85 (Overlay Pavement)
BPR Roughometer = 215 in/mile
Computed From Elevation
Measurements
Power Spectral Density (ft²/cpf)
.001
.0001
.00001
0
.2
.4
Frequency (cycles/ft)

FIGURE (14)

IV. CONCLUSIONS

Further information could have been obtained from the data collected on this project if funds had been available to continue the study. In particular it would have been possible to investigate further the problems associated with the calculation of power spectra from elevation measurements. In this regard it would have been desirable to have had elevation surveys made on sections of considerably longer length than those used in this investigation.

Of fundamental importance in calculating power spectra from any experimental data (elevation measurements, profilometer, servo-seismic system) is the selection of the data processing technique. Further study in this area would be valuable.

As a consequence of this investigation the following conclusions are presented.

A. Power spectra calculate from elevation measurements were less reliable as a criterion of highway condition than were measurements made with other devices including the BPR roughometer. The results of this investigation indicate that the use of a running mean provides a more reliable criterion of pavement condition than does the use of a second order base line when the deviations are

to be determined. Since the length of the running mean was considerably different than the length of the second order base line that was employed, it is difficult to make a direct comparison from the data that are presently available. There is also evidence to indicate that the accuracy of the elevation measurements may not be sufficient to afford the calculation of a reliable criterion of this type.

B. The limited results obtained from information obtained by both the special device operated by the General Motor Corporation and the truck mounted profilometer operated by the University of Michigan indicate that information can be obtained from both of these devices to calculate highway spectra. The comparison between spectra computed from data obtained using these devices and the spectrum calculated from elevation measurements is very encouraging. It is unfortunate that an extremely small number of data had to be used in this phase of the work.

C. The power spectrum appears to be a good way to characterize pavement condition when vehicle response is to be determined, but the data from which a spectrum is to be calculated is a matter for further consideration. Many features of the elevation power spectrum make it attractive as a method for characterizing highway condition. It is evident, however, that certain problems are encountered when such a

characterization is undertaken from highway elevation measurements. It may be more feasible, however, to obtain highway power spectra from the response of special test vehicles properly designed for this purpose than by calculating such spectra from elevation measurements made under the usual field conditions.

REFERENCES

1. Yoder, E. J., and Milhous, R. T., "Comparison of Different Methods of Measuring Pavement Condition." (Final Report for NCHRP Project 1 - 2.)

2. Quinn, B. E., and Thompson, D. R., "Effect of Pavement Conditions Upon Dynamic Vehicle Reactions." Bulletin No. 328, Highway Research Board, (1962).

3. Quinn, B. E., and Van Wyk, R., "A Method for Introducing Dynamic Vehicle Loads Into the Design of Highways." Proceedings, Highway Research Board, Vol. 40, p. 111, (1961).

4. DeVries, T. W., "A Statistical Method for Estimating Dynamic Vehicle Loads on Highways". Thesis - Ph.D., 1961, Purdue University.

5. Thompson, W. E., "Measurements and Power Spectra of Runway Roughness at Airports in Countries of the North Atlantic Treaty Organization." Technical Note 4303, National Advisory Committee for Aeronautics, July 1958.

6. Blackman, R. B., and Tukey, J. W., "The Measurement of Power Spectra." Dover Publications, Inc. (1958).

7. Quinn, B. E., and Wilson, C. C., "Can Dynamic Tire Forces Be Used as a Criterion of Pavement Condition?" Record No. 46 (1964) Highway Research Board

8. Quinn, B. E., and Zable, J. L., "Evaluating Highway Elevation Power Spectra From Vehicle Performance" presented at Annual Meeting, 1965, Highway Research Board, (To be Published).

9. Housel, W. S., "Cumulative Changes in Rigid Pavements With Age in Service." Bulletin 328 (1962), p. 3, Highway Research Board.

10. Spangler, E. B., and Kelly, W. J., "Servo-Seismic Method of Measuring Road Profile." Bulletin 328 (1962), pp. 33-51, Highway Research Board.